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THERMAL PROPERTIES OF POLYPROPYLENE FIBRILLATED FIBRE REINFORCED LIGHTWEIGHT FOAMED CONCRETE

The global demand for energy has experienced a significant rise. The thermal performance of conventional concrete has been extensively studied, but there is still a significant amount of research needed to understand the effects of synthetic fibres on the thermal properties of lightweight foamed concrete (LFC). LFC popularity in the construction industry has increased rapidly due to the many benefits it offers over conventional concrete. Therefore, the goal of this study is to investigate the feasibility of incorporating polypropylene fibrillated fibre (PFF) into LFC to improve its thermal properties. The PFF was integrated into the LFC in diverse weight fractions, between 1% to 4%. Density of 1080 kg/m^3 was made and evaluated. Spreadability, permeable porosity, conductivity, diffusivity and specific heat capacity were determined. The findings demonstrate that spreadability of fresh mix decreased when the weight fractions of PFF were increased from 0% (250 mm) to 4% (239 mm). The incorporation of 3% PFF to LFC greatly improves its conductivity and diffusivity. Specifically, the thermal conductivity decreases from 0.3307 W/mK (in the control) to 0.2643 W/mK, and the diffusivity decreases from 0.4426 m^2/s (in the control) to 0.3843 m^2/s. Compared to the control specimen, LFC's porosity increased slightly from 43.6% to 44.9% when 3% PFF was added. The findings revealed that the PFF possesses significant underlying potential for utilisation in cementitious materials, potentially serving a pivotal function in either reducing the thermal-inducing property or improving the heat transfer of the concrete. The utilisation of LFC-PFF composites may also result in significant energy savings.

Keywords: Foamed concrete; polypropylene fibrillated fibre; thermal properties; thermal diffusivity; specific heat capacity

Nomenclature

LFC – Lightweight Foamed Concrete
PFF – Polypropylene fibrillated fibre
OPC – Ordinary Portland cement

1. Introduction

Lightweight foamed concrete (LFC) exhibits a relatively minimal tensile strength, restricted flexibility, and constrained defiance to cracking [1,2]. Concrete inherently contains internal micro-cracks, which result in a decrease in its tensile strength and ultimately lead to brittle fracture [3,4]. The concrete has undergone restraint, and traditional strengthened steel bars have been employed to enhance LFC tensile characteristics [5]. While these methods enhance LFC tensile strength, they do not elevate the inherent tensile strength of the concrete material itself [6,7]. The incorporation of closely packed, evenly distributed fine fibres into concrete would function as a fracture inhibitor, leading to substantial enhancements in both the dynamic and static characteristics of LFC [8,9]. Hence, the incorporation of fibre-reinforced LFC presents a viable solution to address the challenges associated with insufficient tensile strength, toughness, combustibility, resistance to impact, and resilience [10,11]. The thermal characteristics of LFC are a significant consideration in building facade where variations in temperature may arise due to environmental factors or other causes [12-14]. A comprehensive understanding of the thermal expansion characteristics of LFC is essential for the successful design [15] and construction of various mass concrete structures [16]. These structures include but are not limited to dams, airport flight strips, roadways,

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bridge support systems accommodating horizontal and vertical movements, as well as statically indeterminate structures that experience temperature fluctuations [17].

The adoption of LFC as a construction material has witnessed substantial expansion within the Malaysian construction industry [18]. This may be attributed to its several advantageous characteristics, including its reduced weight, ease of manufacturing, cost-effectiveness, and durability [19]. LFC is a type of lightweight material that is fabricated of OPC and possesses a uniform pore structure, which is achieved by including microscopic air bubbles in the mixture [20]. By employing specific methods and controlling the foam quantity, a wide range of densities can be made, extending from 580 to 1980 kg/m^3, can be achieved [21]. The global interest in environmentally friendly building materials has stimulated extensive study on green concrete worldwide [22]. Considerable attention has been directed to several aspects including mix proportions, sourcing of mix materials, construction approaches and technology, and maintenance of concrete structures.

Hence, the achievement of sustainable development within society is contingent upon the substantial contribution made by industrial stakeholders. In general, most construction materials are produced from non-maintainable sources, resulting in significant energy consumption, and contributing to global environmental challenges. Therefore, the use of synthetic fibre into LFC has the potential to address these challenges [23]. The utilization of LFC in construction has numerous advantages, including effective thermal insulation, remarkable fire resistance, reduced weight, and decreased consumption of ingredients such as OPC, fine filler, foam, and water [24].

LFC exhibits reduced weight as a result of the omission of aggregates, rendering it a concrete variant characterized by good spread ability, low content of binding material, and reduced aggregate utilization. Moreover, it can also be categorized as environmentally sustainable, readily manufacturable, and combustible. However, to accomplish the required density of LFC, it is necessary to extend the mixing duration to ensure proper blending of the components [25]. The use of synthetic fibre in LFC enhances its thermal and mechanical properties. In previous studies, it has been demonstrated that a decrease in the volumetric proportion of short synthetic fibres can mitigate the influence of early age factors on the long-term durability of LFC [26]. The increasing prevalence of foams has facilitated the broader use of LFC for various applications such as roof insulation, floor screed, and concrete blocks.

The LFC thermal conductivity is comparatively lower than that of normal strength concrete, with values ranging from 0.1-0.7 W/mK for a density ranging from 300 kg/m^3 to 1600 kg/m^3 [27]. The improved LFC thermal conductivity is attributed to the presence of air spaces inside the material, which impede the transport of heat by preventing the movement of air. The presence of trapped air in LFC contributes to its exceptional thermal insulating characteristics, resulting in the formation of thermal barrier [28]. While a decrease in the LFC density can possibly result in a decrease in thermal conductivity. LFC undergoes the formation of small cracks during the curing process, which then quickly spread when subjected to external forces, leading to a decrease in its ability to withstand tension [29]. Decreasing the density of foamed concrete also leads to an increase in the number of micro-cracks. Studies have shown that foamed concrete with a density of 500 kg/m^3 develops a greater number of micro-cracks compared to foamed concrete with a density of 1000 kg/m^3 [30,31]. The mechanical properties of foamed concrete are influenced by the formation of micro-cracks.

Awang and Ahmad [32] examined the variances between synthetic and natural fibres at weight fractions of 0.25% and 0.40%. The additives employed were glass fibre, polypropylene fibre, steel fibre, kenaf fibre and oil palm fibre. Regarding thermal properties, the study found that polypropylene fibre had the highest performance, subsequently followed by kenaf, oil palm, glass and steel fibres, in that specific sequence. The experimental outcomes indicate a significant connection between an enhancement in the fibre weight fraction and an increase in the thermal properties of LFC. Raj et al. [33] found that the efficiency of FC might be enhanced by using polyvinyl alcohol fibres and coir fibre. LFC reinforced with coir fibre exhibited superior performance compared to LFC reinforced with polyvinyl alcohol fibre, which in turn exceeded LFC strengthened with a hybrid composite of polyvinyl alcohol and fibres.

The identification of the quantities of synthetic fibres, binder, filler, water, and surfactants within the blend is of utmost importance. Synthetic fibres possess numerous advantages in comparison to some natural fibres. Synthetic fibres exhibit a low density, contributing to their lightweight nature. Furthermore, synthetic fibres demonstrate a high resistance to melting when subjected to heat [34]. The exploitation of synthetic fibres in the reinforcement of cementitious constituents has been observed to be particularly effective in the development and fabrication of construction materials.

Polypropylene fibrillated fibre (PFF), a type of synthetic fibre, shows promise as an additive for enhancing the thermal properties of LFC. The high durability attributes, alkali resistance, and thermal properties of the PFF membrane collectively impact to its outstanding occurrence. Furthermore, the PFF layer is recognized as a fibrous material that may be integrated into a cement composite with exceptional defiance to fracture [35]. The integration of PFF within LFC facilitates the establishment of a comprehensive network of dispersal in three dimensions [36], so effectively mitigating the propagation of microcracks in materials composed of cement.

According to the review above, it appears that LFC might considerably benefited from integrating PFF. This study examined the impact of utilizing PFF in LFC on the spreadability, thermal properties and porosity of LFC. This was achieved by measuring the slump flow, apparent porosity, thermal conductivity, thermal diffusivity and specific heat capacity of the LFC. The impact of different weight fractions of PFF on thermal properties of LFC was assessed. The novelty of this experimental inquiry is to enhance the comprehension of the thermal characteristics of PFF-LFC hybrids. At present, there is a lack of knowledge gap about the properties of medium-density LFC (1000-1200 kg/m^3) that is fortified with PFF at various weight fractions. The utilization of low-cost additives such as PFF holds significant importance nowadays. Specifically, there is a growing need to investigate and broaden the use of new cement-based materials for various purposes within the building sector.

2. Experimental setup

2.1. Materials

The primary materials employed in this study included of meticulously sieved river sand, possessing a specific gravity of 2.61 g/cm^3 and particle sizes spanning from 0.14 to 2.35 mm. Additionally, OPC that adhered to the standards set by the BS197-1 was employed. The complete amount of river sand required was subjected to a sieve analysis in order to meet the specifications for coarse aggregate outlined in ASTM-C33. Furthermore, the utilization of a surfactant derived from proteins resulted in the successful generation of a foam that exhibited a consistent density of 72 kg/m^3. Subsequently, the LFC mixtures were supplemented with four distinct weight fractions of PFF (as depicted in Fig. 1), spanning from 1% to 4%. The PFF properties are presented in TABLE 1.

Fig. 1. Polypropylene fibrillated fibre (PFF) utilized in this study

TABLE 1

Polypropylene fibrillated fibre (PFF) properties

Properties	Value
Young's elasticity (GPa)	7.19
Elongation at break (%)	20.5
Tensile strength (MPa)	885
Weight (g/cm^3)	0.91
Width (mm)	0.19
Length (mm)	25
Conductivity (W/mK)	0.244
Melting point (°C)	155

2.2. Mix design

A set of five LFC blends with a density of 1080 kg/m^3 was generated. The weight fraction of PFF consumed ranged from 0% (control) to 4%, with increments of 1% between each concentration. A control LFC was also prepared without the inclusion of PFF for the purpose of comparison. The selection of a PFF weight fraction ranging from 1% to 4% was based on the findings of a preliminary investigation, which revealed that including a PFF weight fraction over 4% resulted in undesirable outcomes of accumulation and non-even scattering of PPF in the LFC mix. A sand-to-cement fraction of 1:1.5 was occupied, while a consistent water-cement ratio of 0.48 was maintained across all the blends. TABLE 2 presents the mix proportions of LFC-PFF composites utilized in this study. The workability of each mix was checked via the spreadability test shown in Fig. 2. The flow diameter should be maintained in the range of 240-250 mm.

Fig. 2. Spreadability test executed on each fresh LFC-PFF hybrid mix

TABLE 2

LFC-PFF composites mix proportions

Sample	Density (kg/m^3)	PFF (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)
Control	1080	0.00	396.8	595.3	198.4
PFF1	1080	11.91	396.8	595.3	198.4
PFF2	1080	23.81	396.8	595.3	198.4
PFF3	1080	35.72	396.8	595.3	198.4
PFF4	1080	47.62	396.8	595.3	198.4

3. Experimental Setup

The thermal constant analyzer, known as the hot disc, utilizes the TPS method as outlined in the BS22007-2 standard. This instrument was employed to conduct measurements of diffusivity, specific heat and conductivity throughout the experimental test. The dimensions of the sample utilized were 30×30 mm, with a thickness of 10 mm. It is imperative that all specimens to be analyzed are in a state of dryness. The parameters, including probing depth, time, and power, must be established, and maintained at a consistent and acceptable level. The specimens utilized in each test were acquired following a 28-day curing period of the batch mixes. Once the samples have been divided into pairs, they undergo a series of procedures including smoothing, sandpapering, blowing with an air blower, and drying. Two samples with equal dimensions were subjected to a controlled temperature of 76±5°C in an oven for a duration of 48 hours, or until a state of constant weight was achieved. This process was carried out to completely eliminate any moisture present in the samples. For each LFC-PFF batch, three identical samples were made and tested, and their average values have been calculated and reported. Fig. 3 shows the setup for the thermal test.

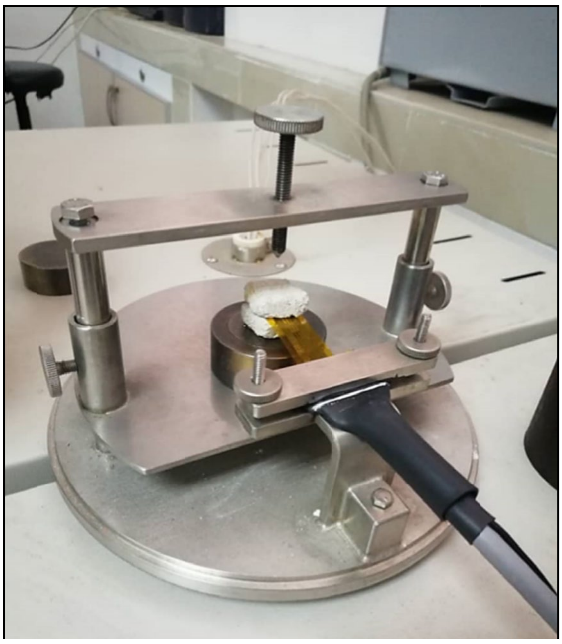

Fig. 3. Setup for thermal test

Furthermore, a permeable porosity test was performed utilizing a vacuum saturation device. The dried specimens underwent a process of exposure to a vacuum environment within a desiccator for a period of three days. During that specific time frame, the desiccator was filled with water that had been de-aerated and distilled. The specimens underwent regulated environmental conditions within a ventilated oven, where the temperature was maintained at 105°C for a period of three days. The purpose of this study was to ascertain the mass of the specimens following the full elimination of moisture, a condition often known as the oven-dry mass. Following this, the specimens were removed from the oven and left to cool down to the surrounding room temperature. The purpose of conducting weight measurements on the specimens is twofold: firstly, to ascertain their oven-dry mass, and secondly, to facilitate their subsequent vacuum saturation. In the interim, the vacuum line connector establishes a connection with a pressure gauge, facilitating the initiation of a vacuum pumping process that will last for a duration of three days. Three specimens from each batch were examined to ascertain the apparent porosity; the average value was then used to determine the final results. Fig. 4 demonstrates the permeable porosity test.

Fig. 4. Permeable porosity test via vacuum saturation technique

4. Results and discussion

4.1. Spreadability

Fig. 5 displays the slump flow of LFC mixtures with varying weight fractions of PFF. Clearly, maintaining a fixed water-cement ratio of 0.48 throughout the mixtures resulted in a decrease in slump flow as the weight fractions of PFF increased from 1% to 4%. The control LFC achieved a slump flow of 250 mm without the addition of PFF. Upon adding 1%, 2%, 3%, and 4% of PFF to LFC, the spreadability of the mixtures decreased to 246 mm, 244 mm, 242 mm, and 239 mm, respectively. This is mostly due to the increased weight fraction of PFF, which results in a greater water need for the base mix. Consequently, the slump flow of the LFC mix with PFF was reduced compared to the control LFC mix. The finding of this research aligns with the results of Mydin et al. [37], who utilized synthetic twisted bundle macro-fibres in LFC. Increasing the weight fraction of PFF leads to greater flow resistance and reduced flowability due to the expansion of tangling and resistance between PFF and cement. This ultimately causes a significant drop in spreadability. Increasing the weight fraction of PFF in the base mix of LFC results in a greater propensity for internal resistance in the fresh LFC mix.

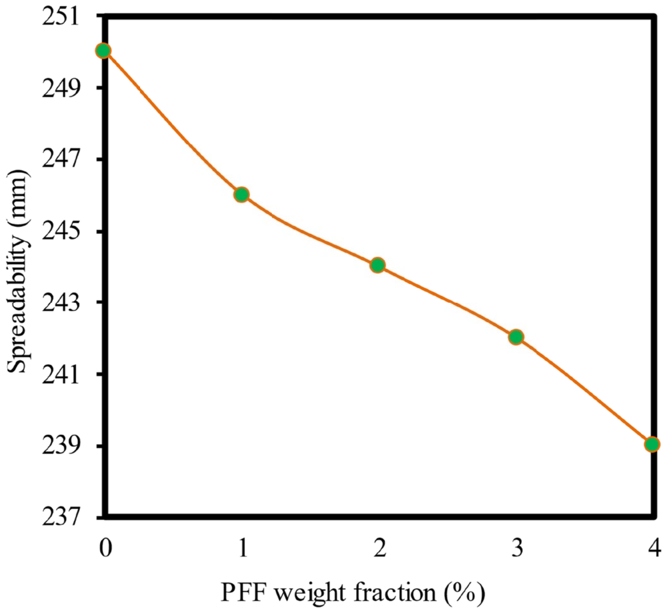

Fig. 5. Spreadability of varying FC-PFF mixtures

4.2. Permeable porosity

Fig. 6 illustrates the relationship between the permeable porosity of LFC and the increasing proportions of PFF. In general, the incorporation of PFF into the composite material of LFC resulted in a slight increase in its porosity. This porosity attains its highest value when the PFF content is increased by 3%. When comparing the LFC mix containing 3% PFF to the control LFC, it was observed that the former achieved the highest porosity values, reaching approximately 44.94%. The control LFC sample logged a permeable porosity of 43.6%. The percentage of increase attained was approximately 2.98%. The observed phenomenon may be attributed to the significant packing efficiency exhibited by PFF within the cementitious matrix of LFC. Microcracks were observed to develop on the surface of the LFC during its initial state of freshness. Simultaneously, the evaporation process of surface moisture occurred fast, leading to notable dry shrinkage. The addition of PFF to LFC mixes has been found to mitigate segregation, hence resulting in a reduction in water loss through evaporation. Furthermore, empirical evidence has demonstrated that the implementation of PFF is an effective measure in mitigating the propagation of surface-initiated cracks inside LFC. Guochen et al. [38] found that the changes in the morphology and form of the PFF cause a small increase in the porosity of LFC. Jhatial et al. [39] discovered that increasing the volume fraction of fibre in cement-based material led to connect the matrix, hence increasing the porosity of LFC.

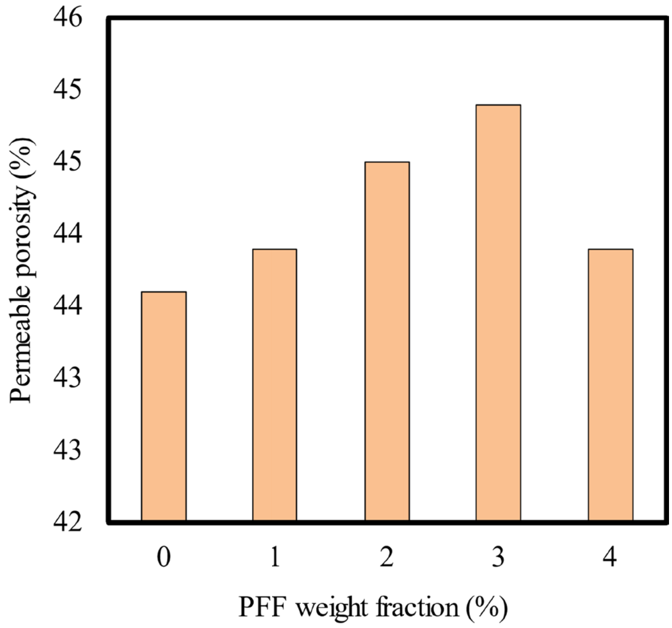

Fig. 6. Permeable porosity of LFC-PFF composites

4.3. Thermal conductivity

Fig. 7 depicts the results obtained from the investigation of the thermal conductivity of LFC with different weight percentages of PFF. The findings of this investigation have provided

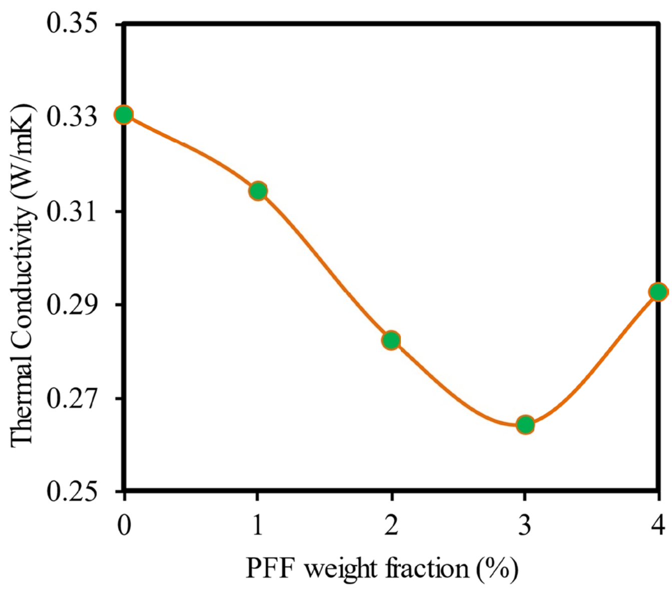

Fig. 7. Thermal conductivity of LFC-PFF composites

confirmation that the incorporation of PFF throughout all weight fractions resulted in enhanced conductivity results when associated with the control LFC sample, which exhibited a conductivity value of 0.3307 W/mK. The inclusion of a 3% proportion of PFF yielded the most favourable outcome in terms of conductivity. The measured conductivity was determined to be 0.2643 W/mK. In contrast, the conductivity of LFC containing a weight proportion of 4% PFF was found to be higher than that of the sample containing a weight fraction of 3% PFF. The non-homogeneous dispersion of PFF inside the polymer matrix of the LFC could potentially be a significant factor, especially once it has attained its ideal volume fraction of 3%. The decline in thermal conductivity as the proportion of PFF increases, reaching the ideal weight fraction, can be ascribed to the porous nature of PFF. Additional factors contributing to the significantly reduced heat conductivity in LFC composites include the redistribution of particles and the formation of smaller, more uniformly distributed pore voids resulting from the incorporation of PFF.

The findings of this investigation are comparable to the findings that were obtained by Liu et al. [40]. Their conclusion was that the molecular structure of air, which exhibits poorer thermal conductivity compared to solid and liquid materials, results in reduced thermal conductivity in porous concrete like LFC. The introduction of PFF in the LFC resulted in the generation of a higher quantity of separated voids in comparison to the control LFC. The findings also indicated that the PFF exhibits significant potential for application in LFC. It can effectively contribute to the reduction of conductivity or heat transmission in manufactured LFC.

4.4. Thermal diffusivity

Fig. 8 illustrates the diffusivity outcomes of LFC reinforced with varying proportions of PFF. According to the data presented in Fig. 8, there is an inverse relationship between the weight fraction of PFF and the thermal diffusivity, whereby a rise in the former leads to a reduction in the latter. As the PFF weight fraction grows from 0% to 3%, there is a corresponding decrease in the thermal diffusivity from 0.4426 to 0.3843 m^2/sec, respectively. According to Brady et al. [41], the integration of PFF into LFC contributes to the mitigation of thermal diffusivity due to the inherent property of PFF having a low thermal conductivity. The LFC diffusivity can be characterized as the ratio of its thermal conductivity to its volumetric heat capacity. The thermal diffusivity of the LFC refers to the rate at which heat can propagate within the composite material. Therefore, when the transfer of heat occurs at a high rate within the material of a composite, it can be classified as a highly efficient thermal conductor. On the other hand, according to Elshahawi et al. [42], if the frequency of heat transmission within the material of a composite is significantly low, it is regarded as a highly effective thermal insulator. The incorporation of the PFF into the LFC results in an increased rate of heat transfer, hence rendering it an exceptional thermal insulating material. Additionally, the incorporation of PFF to LFC-PFF hybrids leads to a reduction in thermal diffusivity owing to the dispersion and formation of smaller, more uniform pore voids. This process led to the creation of a greater number of discrete voids compared to the control LFC specimen without the inclusion of PFF.

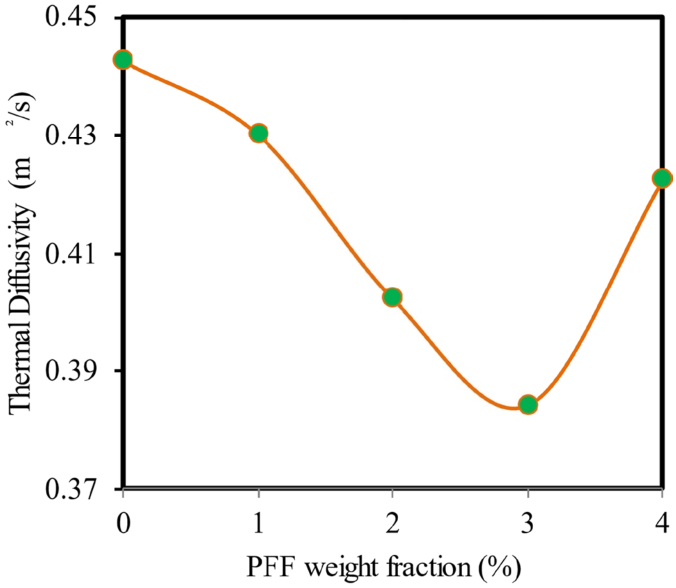

Fig. 8. Thermal diffusivity of LFC-PFF composites

4.5. Specific heat capacity

The quantity of heat energy that is taken in or released by an object per unit mass when its temperature varies by 1 Kelvin is called its specific heat. The property of a substance to effectively store thermal energy and promote energy conservation within structures is implied to as a high specific heat capacity. The specific heat of a material has a significant role in its ability to hold heat and contribute to its thermal mass. Fig. 9 displays

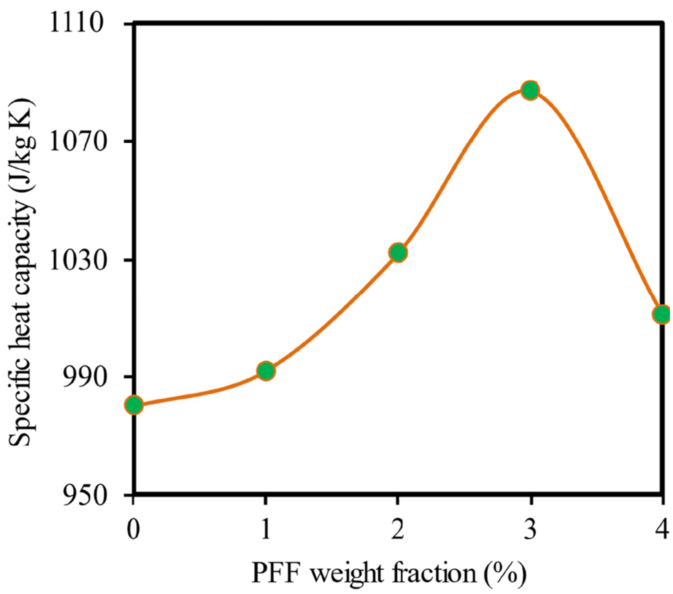

Fig. 9. Specific heat capacity of LFC-PFF composites

the specific heat values of LFC that have been strengthened with varied weight percentages of PFF. When contrasted with the control sample, which displayed a specific heat of 980 J/kgK, the outcomes of this study showed evidence that the integration of PFF across all weight fractions produced a significant increase of specific heat. This was determined through comparing the control sample to the data of this research. The most advantageous result in terms of specific heat was achieved through the introduction of a 3% weight fraction of PFF. The measured value for the specific heat capacity was determined to be 1087 J/kgK. However, the sample containing a weight fraction of 4% PFF exhibited a lower specific heat capacity in comparison to the sample containing a weight fraction of 3% PFF. When added to LFC, PFF causes a rise in the specific heat of cement paste, particularly up to a weight fraction of 3% which is the optimal level. According to Li et al. [43], the rise can be explained by the contact that was produced between the cement and the PFF, which contributes to the specific heat constituents that are related to vibrational aspects.

5. Conclusions

The objective of this experimental study was to examine the thermal characteristics of LFC by including different weight percentages of PFF. The LFC density was measured to be 1080 kg/m^3. The sample was then subjected to testing using five different weight fractions of SF, specifically 0%, 1%, 2%, 3%, and 4%. The following conclusions can be drawn based on the results of this study:

1. When the weight fractions of PFF rose from 1% to 4%, slump flow decreased in all of the mixtures while the water-cement ratio remained constant at 0.48.
2. Incorporating PFF into the LFC led to a marginal increase in apparent porosity. When the weight fraction of PFF was increased to 3% in the LFC mix, the porosity reached its maximum value of around 44.94%, compared to the control mix which had a porosity value of 43.61%.
3. The experimental findings demonstrated that the optimal incorporation of 3% of PFF yielded the most favourable outcomes in relation to the thermal properties, specifically diffusivity, conductivity and specific heat. The attainment of optimal compaction and uniformity in the mixture was seen when the fibres and cementitious matrix attained a weight fraction of 3% of PFF.
4. With the addition of 3% PFF to LFC, the thermal conductivity and diffusivity both decrease from 0.3307 W/mK (control sample) to 0.2643 W/mK and 0.4426 m^2/s (control sample) to 0.3843 m^2/s, respectively,
5. Accumulation and undeviating scattering of PFF were found beyond the optimal amount of PFF inclusion, resulting in a decrease in the overall thermal characteristics that were assessed.
6. Presently, the application of cheap additives, such as PFF, is of critical importance. Specifically, there is a growing demand to investigate and broaden the utilization of innovative cement-based materials for various applications in the construction sector, particularly for enhancing the thermal properties of building facades.
7. Further research into the mechanical, structural, transport, and structural properties of LFC is crucial in order to completely substantiate the potential use of PFF as an additive in cementitious materials.

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